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Space Exploration Initiative Technology Needs and Plans

A Report to the United States Senate

Committee on Appropriations
Subcommittee on the Veteran's Administration, Housing and Urban Development, and Independent Agencies

(NASA-TM-108577) SPACE EXPLORATION INITIATIVE TECHNOLOGY NEEDS AND PLANS. A REPORT TO THE UNITED STATES SENATE, COMMITTEE ON APPROPRIATIONS, SUBCOMMITTEE ON THE VETERANS, HOUSING, AND URBAN DEVELOPMENT, AND INDEPENDENT AGENCIES (NASA) 45 p

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Summer 1990

NASA

National Aeronautics and Space Administration
Office of Aeronautics, Exploration and Technology
Washington, D.C. 20546

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CHAPTER 1

Introduction

"First, for the coming decade - for the 1990's - Space Station Freedom - the critical next step in all our space endeavors.

"And next - for the new century - back to the Moon, Back to the future. And this time, back to stay.

"And then - a journey into tomorrow - a journey to another planet - a manned mission to Mars."

PRESIDENT GEORGE BUSH - JULY 20, 1989

With these words President Bush provided a vision for the American people and gave a new strategic focus to the U.S. civil space program: the Space Exploration Initiative. Achieving the objectives of the Initiative - establishing a human outpost on the Moon, exploring the planet Mars, and continuing exploration of the Solar System - is a challenging prospect. Developing the technology essential for exploration will be a significant aspect of this achievement.

The 1989 National Space Policy, establishing the goal of expanding human presence and activity beyond low Earth orbit, together with President Bush's directives calling for a "long-range, continuing commitment" to exploration, define a challenging framework which requires a new and enduring emphasis on space technology. To meet this challenge, exploration technology development must be a sustained national endeavor. It must provide capabilities for initial exploration missions, establish processes to spawn new developments over time, and create a renewable foundation of innovative technology that will reduce substantially the risks and costs, and increase performance, to enable future exploration missions.

The U.S. Senate Committee on Appropriations requested in Senate Report 101-128, accompanying H.R. 2916, the fiscal year 1990 VA-HUD-Independent Agencies appropriations bill, that NASA provide a report on "what specific technologies will be needed to meet the development and operational requirements of the President's space initiative," including a prioritization of these exploration "technologies from both a technical and a financial standpoint." In response to that request, this report describes NASA's current understanding of the top-level technological challenges of a robust, long-term Space Exploration Initiative and an approach to planning and implementing an Exploration Technology Program to best achieve the Nation's exploration objectives.

We note that no specific mission architecture has been selected nor is such a selection anticipated for at least several years, thus all analysis and evaluation in this report should be considered preliminary and subject to change.

SECTION 1.1

Exploration Initiative Technology Needs

Lunar. A return to the Moon will involve a number of program phases, each of which builds toward the next and contributes to the long-term exploration objective of expanding human presence to the Moon and on to Mars. Our mission experience and technological inheritance from the Apollo program would permit us to stage straight-forward, short-term expeditions to the Moon. However, establishing a long-term lunar outpost will require major advances in engineering capabilities for lunar surface systems, space transportation and low Earth orbit operations, as well as considerable mission planning. The architecture of a Lunar Outpost is envisioned to be, by design, a continuously evolving concept. In addition to planning for this essential capability to evolve, there are a number of major issues associated with an Outpost architecture that must be resolved. Initially, we must transport astronauts, transfer vehicles, equipment and supplies from the surface of the Earth into space. From Earth orbit, expeditions must be, in turn, assembled and/or launched toward the Moon, some 240,000 miles away. Once in the proximity of the Moon, travelers and equipment must be transported safely down to precise locations on its surface. A considerable build-up of local capabilities will be required before extensive surface operations can be realized. Obviously, return transportation from the Moon's surface to the Earth is essential, as are capabilities for life support and effective communications, such as voice, video and computer data transmissions.

At the present time, innovative mission approaches and technology concepts for a Lunar Outpost are being conceived. However, it is clear that timely advances are needed across a number of major technology areas in order for such a program to succeed. Many of these technology areas parallel those in which progress must be made to succeed in exploration of Mars. Thus, by developing capabilities for the Moon, this phase of the Space Exploration Initiative will help build toward the next phase.

Mars. Concurrent with establishing a Lunar Outpost, a series of increasingly capable robotic missions may be staged to renew our exploration of Mars. These missions can serve to develop the scientific, environmental, engineering, operational and technological foundation upon which subsequent human missions will be based. Following a period of robotic studies, the first human expedition to Mars will be staged. This endeavor will mandate developments well beyond today's state-of-the-art in many areas of technology. Human expeditions to Mars will use many of the systems and much of the technology developed for, and tested during operations of the lunar phases of the program. They also will apply technology from the robotic phases of Mars exploration.

As in the case for establishing a Lunar Outpost, there are many issues to resolve in the architectural design of a program to explore Mars. Transportation is the first and foremost concern. We must transport astronauts, transfer vehicles, equipment and supplies into space. From Earth orbit, expeditions must in turn be launched toward Mars, not a few hundreds of thousands of miles away, but instead tens to hundreds of millions of miles away. Once near Mars, travelers and their equipment must be transported safely and accurately down to predetermined sites on the Martian surface. Surface exploration efforts will vary from mission to mission, but will be characterized by major scientific investigations that will play a predominant role in all activities. Communications, return transportation and astronaut life support will be essential. The final architecture of the Mars program will reflect lunar mission experience as well as results from earlier robotic missions, and extensive technological and systems development.

Technology Challenges. The lunar and Mars phases of the Space Exploration Initiative embody a set of common functional areas in which exploration mission architectures and designs must be defined to meet specific challenges, and from which major requirements for new and innovative technologies must be derived. These areas include:

- Earth-to-Orbit Transportation
- In-Space Operations
- Space Transportation
- Surface Operations
- Human Support
- Lunar and Mars Science
- Information Systems and Automation

In virtually all Lunar and Mars aspects of the Exploration Initiative, the need for new and innovative technologies stems from the challenges associated with these major functional areas as well as the goals of risk reduction and reliability improvement, cost reduction and performance enhancement.

SECTION 1.2

Exploration Technology Planning

In response to the President's space policy speech of July 1989, NASA conducted a series of studies to synthesize the results of several years of exploration mission studies and to define feasible mission options and their requirements. Results of these studies were presented in a report to the NASA Administrator in November 1989 as a preliminary database. A significant part of this effort was devoted to the identification and assessment of the critical engineering challenges posed by exploration and the key areas where technology development would be required to meet those challenges.

In addition, NASA has built into the program an active search for innovative technological solutions to exploration's challenges and will incorporate promising new technologies as they are deemed advantageous. As Vice President Quayle directed in a December 19, 1989, letter to NASA Administrator Richard Truly, we must *"cast our net widely"* to bring to bear upon the challenge of exploration *"different architectures, new systems concepts, promising new technologies, and innovative uses of existing technologies."* The search for innovative approaches and technologies, and the incorporation of new appropriate concepts into an evolving endeavor, will permeate NASA's implementation of the Space Exploration Initiative. Throughout this process, the Exploration Technology Program will be the principal source of technology development activities for the Exploration Initiative.

This report addresses the range of exploration challenges that NASA has identified to date, and the current planning for exploration technologies that will meet the development and operational requirements of the President's Exploration Initiative. Because of the diverse demands of transporting and sustaining people while they work and live on the Moon and Mars, of implementing significant robotic exploration missions, and of accomplishing the scientific objectives of this endeavor, accomplishing the Space Exploration Initiative will require research and development in a wide range of technology areas.

CHAPTER 2

Exploration Technology Program Summary

SECTION 2.1

Exploration Technology Program Background

Development of innovative technologies that make mission goals achievable, with reasonable risk and at affordable costs will be crucial to the success of the Space Exploration Initiative. There is a strong foundation of planning for exploration research and technology. This includes planning in programs within and external to NASA, each of which contributes to the Exploration Technology Program.

The NASA Research and Technology Base - which includes contracted and in-house discipline research, university programs, and technology and engineering experiments in space - funds basic research in a wide array of space technologies. This program provides a foundation of laboratory facilities, personnel with specialized expertise, and a basic technology program for use in focused exploration technology development. Through the Civil Space Technology Initiative (CSTI), NASA is developing specific technologies that primarily support and enhance Earth orbital missions. CSTI is a focused technology program that includes several element programs in the areas of Transportation, Operations and Science. Two of the CSTI element programs are of particular significance to Solar System exploration planning: the Aeroassist Flight Experiment and the High Capacity Power Program. Coordination with other national programs is discussed in Chapter 5.

In addition to basic and focused research and technology programs, NASA also conducts advanced development efforts for specific flight programs. An example is the advanced development program for Space Station *Freedom* that was conducted during the mid-1980s. Beginning with a foundation of basic research and technology, this program completed development of many of the technologies that have been incorporated into the Space Station Freedom design. At present, however, no major advanced development programs are in place for exploration, with the exception of the Advanced Launch Development (ALD) program. The ALD program is directed toward providing a future national capability for low cost Earth-to-orbit transportation that may support exploration missions. As a part of its efforts within the Space Exploration Initiative, the NASA Office of

Space Flight is planning to significantly increase participation in the ALD program beginning in FY 1991.

The Pathfinder Program, started in FY 1989 and continuing in FY 1990, is a focused program that is directed specifically toward the development of new capabilities and innovative technologies for Solar System exploration. The program is organized into a series of four mission-oriented technology thrusts; Surface Exploration, In-Space Operations, Humans-In-Space and Space Transfer.

Beginning with the FY 1991 budget, the Pathfinder Program has been expanded into the "Exploration Technology Program." This transition reflects substantial reorganization and reassessment, while maintaining the focus and basic character of the program. The Exploration Technology Program is organized according to mission-oriented thrusts. Each of these is intended to encompass the challenges posed by one of the major functional areas of exploration. The definition of these areas, and of the technology activities within them, have been refined and augmented for FY 1991 in support of the Space Exploration Initiative.

Key Technologies to Meet Exploration Challenges

A major challenge to settlement on the Moon and expeditions to Mars is the need to reduce dramatically the total mass that must be launched into low Earth orbit for transport to the lunar and Martian surfaces. Although additional factors, such as crew time, power and servicing requirements are very important, reducing launched mass is an overarching priority to achieve the objectives of long-term self-sufficiency and acceptable operations costs. In the near-term, critical capabilities in regenerative life support, aerobraking, and high-performance, space-based cryogenic engines need to be developed in order to support substantial reduction of the initial mass in low-Earth orbit.

The mid-term technologies of space nuclear power and *in situ* resource utilization on the Moon are critical to decreasing mass to low Earth orbit and increasing self-sufficiency for a Lunar Outpost. In addition, a better understanding must be developed of requirements for radiation shielding in order to design safe, optimum-cost vehicles for human expeditions to Mars. Also, although those human expeditions to Mars can be conducted using cryogenic propulsion and aerobraking, nuclear propulsion presents a compelling opportunity for substantially reducing the mass and travel time required for human expeditions to Mars. Studies strongly indicate that development in each of these seven technology areas - regenerative life support, aerobraking, cryogenic engines, surface nuclear power systems, *in situ* resource utilization, radiation protection, and nuclear propulsion - needs to be pursued aggressively in the near term, because innovative solutions in these areas will have a major impact in enabling exploration mission architectures and schedules.

In addition, the National Research Council, in its Winter 1990 review of NASA planning for the Space Exploration Initiative strongly endorsed technology development in the areas of nuclear power and propulsion; in advanced human-machine systems (including autonomous vehicle maneuvering, sample acquisition, analysis and preservation, surface construction, in-space assembly, planetary rovers, and others); in artificial gravity; and in human support areas such as regenerative life support, radiation protection, and extravehicular activity systems.

The technology assessments provided in this document reflect the current analysis of the requirements for the Space Exploration Initiative. The set of technologies in the program will necessarily be refined as mission scenarios and alternatives mature.

SECTION 2.2

Earth-To-Orbit (ETO) Transportation

Earth-to-orbit transportation has long been recognized as a critical requirement for any substantial civil space program. Mission-level requirements for technology development to support advanced Earth-to-orbit transportation include:

- highly reliable vehicle operations/launch
- reduced Earth-to-orbit launch costs
- increased Earth-to-orbit launched mass

Because of the scope and size of the vehicles, equipment and supplies required for returning to the Moon to stay and of sending humans to Mars, a heavy-lift launch capability is a primary requirement for the Space Exploration Initiative. Reducing the amount of in-space assembly required, and the number of launches needed, for any given phase of the Initiative has the potential to substantially reduce program costs. Areas requiring technology development include: propulsion; avionics and software; structures, materials and manufacturing; aerothermodynamics and system recovery; and operations.

Specific national planning for Earth-to-orbit transportation technology development and the requirements of exploration were assessed during NASA studies. Initial NASA planning for the Space Exploration Initiative concluded that Shuttle-C options and an ongoing joint definition and advanced development program between the Department of Defense and NASA - the Advanced Launch Development (ALD) program - could provide the capabilities needed for the lunar outpost/robotic Mars exploration phase of the Initiative.

NASA is planning to increase its support for the ALD advanced development program in the area of Earth-to-orbit propulsion systems in fiscal year 1991. However, no requirement for a new, focused research and technology program to supplement efforts underway within ALD has been identified at this time. The status and progress of the ALD program, including planning for specific transportation systems development, will be continually assessed - in terms of technology development requirements - because of the great importance of a highly capable heavy lift launch system to the success of the Space Exploration Initiative.

SECTION 2.3

Space Transportation

Technology development for space transportation systems will provide improvements necessary to insure safe, efficient and reliable transportation to and from the Moon and Mars. The key challenges in Space Transportation include reducing propellant and vehicle mass to reduce costs, and also providing capabilities for reliable piloted and automated vehicle operations. Technology development in FY 1991 will focus on:

- low-energy and high-energy aerobraking for both lunar and interplanetary vehicles
- space-based cryogenic engine systems
- autonomous vehicle maneuvering capabilities (including autonomous rendezvous and docking, and autonomous landing)

Based on current planning, several other space transportation technology areas also will require development, including vehicle structures, cryogenic propellant tanks, and artificial gravity.[1]

Aerobraking

The application of aerobraking will substantially reduce mass requirements in low Earth orbit, and therefore is critical for cost-effective transportation of significant masses to the Moon and for Mars mission options.[2] The Aerobraking Program will include integrated ground-based research and technology to complement flight data obtained from the Aeroassist Flight Experiment.

Focused research and technology is needed to provide integrated vehicle configuration analysis as well as technology for specific options for piloted lunar vehicle aerobraking and robotic aerobraking at Mars. This includes development in the areas of materials and structures (thermal protection systems); adaptive guidance, navigation and control; and computational fluid dynamics (CFD) modeling. Aerobraking is a critical technology for the Space Exploration Initiative.

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1. The special space transportation technology topic of advanced nuclear propulsion technologies is addressed in Section 2.9.

2. Throughout Section 2.3 to Section 2.10, a specific and consistent nomenclature is used to describe the currently understood importance of each technology area to the Exploration Initiative. This nomenclature - "critical" to the Initiative, "enabling" for some options, and "high leverage" for some systems - is explained in detail in Section 2.11.

The Aeroassist Flight Experiment (AFE) is a key component of the overall development of aerobraking technology. One of the element programs of the Civil Space Technology Initiative, AFE is a major research and technology flight experiment. It is designed to provide critical in-space data to optimize low-to-moderate energy aerobrake design (including aerobraking in low Earth orbit after a return from the Moon). Like the complementary Aerobraking Program within the Exploration Technology Program, AFE is critical to the success of the Space Exploration Initiative. With a planned flight in 1994, the AFE will provide essential data - which cannot be obtained at a ground facility - to verify fluid dynamics computational analyses, provide data on thermal protection system performance, and test guidance, navigation and control for a specific aerobrake configuration.

Space-Based Engines

Space transportation for the Space Exploration Initiative will include vehicles for moving from one orbit to another, as well as for landing on and ascending from the surfaces of the Moon and Mars. For both types of transportation, high performance and cost efficiency are key challenges that must be resolved for many Space Exploration Initiative architectural options. An advanced, high-performance engine, capable of being maintained in space, will enable reliable and reusable, space-based vehicles for exploration. A focused program to develop space-based cryogenic engines is critical to all Exploration mission options involving space-basing and reusability of vehicles.

The Space-Based Engines Program will formulate design methods for advanced, space-based engines and put in place multiple ground-based, advanced, expander-cycle cryogenic engine testbeds, for development of components for deep throttling, health monitoring, space servicing and aerobrake-compatible (extendible) nozzles.

Autonomous Landing

In a variety of operational scenarios, exploration vehicles will be required to land on a planetary surface in autonomous and semiautonomous modes, with little or no human control of the vehicle due to communications time delays. The capability to land safely at geologically interesting sites while under automated, on-board control is critical to several MARS robotic and human expedition vehicle concepts.

The nearer-term efforts of the Autonomous Landing Program will include research and technology development and demonstration of advanced guidance algorithms, innovative navigation techniques, adaptive control systems, advanced landing sensors and sensor data processing, and landing systems autonomy.

Autonomous Rendezvous & Docking

For robotic Mars sample return missions, spacecraft will need to operate with extended absence of human control of the vehicle orbital maneuvers (for example, up to 40 minute delays). This technology area is enabling for some mission options as well; including automated resupply system concepts for a lunar outpost and future human mission to Mars operations.

The nearer-term efforts of the Autonomous Rendezvous and Docking Program will include research and technology development in the areas of sensors; guidance, navigation and control; mechanisms; and detailed definition of ground and flight demonstrations.

Other Transportation Technology Needs

In addition to the immediate technology requirements discussed above, exploration space transportation research and technology development efforts will also be needed in other areas, such as Vehicle Structures and Cryogenic Tankage, where advances could improve the cost-effectiveness of lunar transportation through additional mass reductions. Another area where specific requirements for research and technology development are still being defined is Artificial Gravity, which may be required to maintain the health of astronauts by ameliorating the long-term effects of low gravity. There are numerous other innovation approaches and technological options for exploration space transportation, which will continue to be studied throughout the course of the Initiative.

SECTION 2.4

In-Space Operations

The Space Exploration Initiative will rely on movement of equipment, personnel and supplies from the surface of the Earth, through low Earth orbit, and on to the Moon or Mars. For any given Earth to orbit transportation system, some degree of on-orbit assembly and maintenance of exploration vehicles is required to achieve reusability. Similarly, space-basing of exploration vehicles depends on the capability to refuel and to store propellants over time in space. Accommodation of Earth-orbit operations is projected to be a primary responsibility of Space Station *Freedom* in several exploration mission scenarios. Advances in several technology areas are clearly needed to provide key capabilities for in-space operations, such as Earth-orbit staging of large-scale human missions to the Moon and Mars. These areas include:

- in-space assembly and construction
- in-space vehicle processing and servicing
- cryogenic fluid systems (for long-term storage and vehicle transfer)

Cryogenic Fluid Systems

The in-space refueling of exploration vehicles and the long-duration storage of cryogenic propellants in space and on the lunar surface will be enabling for human exploration missions to the Moon and Mars. Essentially all of the exploration mission concepts studied to date have required advanced cryogenic fluid systems including capabilities for fluid and/or tank transfer, long-term storage and efficient refrigeration and/or liquefaction. This technology area is therefore enabling for many of the architectural and mission options that are possible for the Space Exploration Initiative; it is required for projected long-duration flights, to refuel spacecraft in space, and to store cryogenic fluids (such as liquid oxygen for propellants or for life support) on the Moon.

Present research and technology must be augmented to meet mission technology requirements in this important area. The Cryogenic Fluid Systems Program includes computer modeling development of variable gravity cryogenic fluid systems, development of various components for cryogenic fluid systems such as supply systems, transfer systems and instrumentation; pressure control; thermal control systems; and definition of required technology validation in space.

In-Space Assembly and Construction

Due to the limitations of current and projected launch vehicles, in-space assembly and construction (typically in low Earth orbit) will be essential to our ability to stage large-scale exploration vehicles. For human Mars expedition mission options, this technology area is enabling. On-going focused technology activities must be refined and augmented. The In-Space Assembly and Construction Program includes research and technology development and demonstrations to support low Earth orbit exploration vehicle staging, particularly in the areas of mechanical joint concepts, permanent joining and bonding, utilities installation, manipulator concepts, dynamics and controls. Preliminary development of an advanced space crane for precision manipulation of the large and massive systems also is needed.

Vehicle Servicing and Processing

The capability to provide vehicle servicing and processing in low Earth orbit and on the lunar surface will be an integral aspect of any long-term strategy for human exploration. This technology area is enabling for Space Exploration Initiative options that rely on space-basing of vehicles and systems (i.e., advances in these capabilities are essential to the design of such systems). A new research and technology program is needed in this area to support capabilities for space-basing of lunar outpost mission operations. The nearer-term efforts in the Vehicle Servicing and Processing Program include development of technology for integrated automated check-out and testing, semiautonomous nondestructive inspection and evaluation (NDI/NDE), automated utilities inspection, telerobotic manipulators for servicing, and the definition of preliminary design-for-servicing guidelines and requirements for technology experimentation and demonstration in space.

SECTION 2.5

Surface Operations

In a very real sense, surface operations are the primary purpose of the Space Exploration Initiative. Both the expansion of human presence and the conduct of significant scientific studies will depend on our ability to execute new and ambitious lunar and Mars surface operations with high reliability. At the same time, operations costs for these activities must be held within reasonable limits. Achieving these objectives requires technology developments in:

- space nuclear power
- *in situ* resource utilization
- planetary rovers (with surface mobility systems)
- surface solar power (with chemical energy storage)
- surface construction and habitats.

Space Nuclear Power

Due to the long lunar night, space nuclear power on the lunar surface is enabling for any operational scenario that involves extensive operation at a Lunar Outpost. This technology area, therefore, is critical to the overall implementation of the Space Exploration Initiative and to the establishment of a largely self-sustaining Lunar Outpost - within reasonable bounds of cost. The SP-100 is an existing focused national technology project in this critical area.

The Space Nuclear Power Program will continue the development of the ongoing SP-100 Ground Engineering System, with strengthened content in non-reactor subsystem technologies, including power conversion, heat rejection and thermal management, and power management and distribution. This program will also integrate ongoing activities in the development of advanced thermoelectric and dynamic conversion technologies and the investigation of other space nuclear power technology requirements for the Space Exploration Initiative. The SP-100 program is a major national effort, supported by NASA and by the Department of Defense, and managed by the Department of Energy.

The High Capacity Power Program is one of the focused research and technology programs of the Civil Space Technology Initiative. Through this program, NASA is developing advanced, high-performance and high-efficiency thermal-to-electric power conversion (including free piston Stirling engines and improved solid state converters), and thermal management technologies. This technology has potential application to provide enhancements to the baseline SP-100 program technologies, allowing generation of more electrical power with the same reactor system. This area is enabling to meet the requirements of many of the mission options within the Space Exploration Initiative.

In Situ Resource Utilization

The logistics associated with a Lunar Outpost are sufficiently complex that there is enormous potential leverage in utilizing *in situ* resources wherever possible. One such possibility lies in offsetting the substantial transportation requirements for liquid oxygen (needed for propellants and life support systems) associated with significant Lunar Outpost operations by using available high levels of power for local manufacture of this resource. Such *in situ* resource utilization (ISRU) is critical for exploration. By dramatically reducing logistics transportation requirements and costs it is enabling for many of the specific mission options under study, for example, a largely self-sufficient Lunar Outpost. As a side benefit to extracting oxygen from the lunar soil for propellants, it also may be possible to use waste materials from the processing operations to produce construction materials for the outpost. (See the discussion below of Surface Habitats and Construction.) A new, focused technology development program is needed in this area. The near-term program will provide the development of technologies for mining systems and for lunar soil use. In addition, approaches to processing lunar materials efficiently to extract valuable resources will be examined and developed.

There will be a limited number of astronauts on the Moon when resource processing operations begin and capabilities that may be expected from advanced Lunar Outpost spacesuits will still be limited. Thus, developing capabilities for robust and largely automated operations with a minimum of maintenance is essential to the application of *in situ* resource utilization at a Lunar Outpost.

Planetary Rovers

The capability for piloted and robotic surface mobility will substantially enhance the scientific return from a long-term exploration program, as well as enable several mission operational scenarios. (For example, *in situ* resource utilization on the Moon will depend upon mobile mining systems.) This technology area therefore is enabling for many of the mission options within the Space Exploration Initiative - in particular, for robotic Mars missions and for advanced Lunar Outpost operations. A focused research and technology program is needed in this area to meet the needs of both piloted and robotic missions options.

The near-term efforts in the Planetary Rovers Program will develop and apply advanced robotic technologies. These include technologies such as autonomous system executives, terrain sensing systems and semiautonomous navigation systems. The program also will begin breadboard demonstration of required operational capabilities for possible lunar outpost scenarios, including mobility systems for applications in lunar mining and lunar construction.

Surface Solar Power

Although nuclear power is necessary for a largely self-sufficient Lunar Outpost, lunar surface solar power is needed to provide for start-up prior to installation of space nuclear power. Solar power technologies also can provide a back-up source of power even after nuclear systems are on-line. In addition, advanced fuel cell technologies are needed to power mobile vehicles. State-of-the-art power systems for long-duration, space-based mission operations include limited power levels from current photovoltaic (PV) array and power management technologies, and limited power storage from current battery systems. Lunar systems based on these technologies would require major investments in system mass, and hence, costs. Advanced solar power technology is enabling for several of the Lunar Outpost mission options. A focused technology development and demonstration effort is needed in this area.

The near-term efforts in the Surface Solar Power Program will develop required regenerative fuel cell technologies for lunar applications and initiate the development of advanced photovoltaic array and power management technology, including the definition and initial development of breadboards for system technology performance and reliability testing and verification.

Surface Habitats and Construction

Keeping the crew productive during any extended human presence on the Moon or Mars will require suitable provisions, such as acceptably spacious living quarters. Many studies have proposed a cost-effective way of using habitats that are locally constructed. This could include innovative concepts such as inflatable structures or tunneling into the lunar regolith (soil) to create living space. It also may include using locally manufactured building materials (as noted above in the paragraph on *In Situ* Resource Utilization). In addition, many projected outpost systems must be transported in a packaged configuration and then assembled on the planetary surface following arrival. Thus, the ability to assemble and/or construct surface habitats and other systems on the planetary surface is enabling for many of the system concepts being considered as part of the Space Exploration Initiative. However, no technology base exists in this important area of Surface Operations.

A new focused research and technology program is needed in order to enable required capabilities for a family of human Lunar Outpost mission options. Near-term efforts in the Surface Habitats and Construction Program will include definition of habitat concepts, development of habitat materials and structures, development of innovative connections for lunar surface utilities, definition of construction equipment concepts, and development of preliminary construction equipment end-effectors and tools.

SECTION 2.6

Human Support

While a foundation of Space Shuttle and Space Station Freedom systems already exists, the demands of deep-space expeditions and of a permanent outpost on the Moon require the development of technology for the long-term support of people on these exploration missions. The Exploration Technology Program will provide new capabilities and the understanding needed to insure safe and productive long-term human participation in the Space Exploration Initiative. These are capabilities intended for both extended surface operations on the Moon and Mars and long-duration space flight and include[3]:

- regenerative life support
- radiation protection
- extravehicular activity (EVA)
- exploration mission space human factors (such as advanced man-machine interfaces)

Regenerative Life Support

Human expeditions to Mars conceivably could be conducted using open-loop life support with no recycling. However, establishing a permanent human presence on the Moon, or reducing the cost of Mars expeditions, would require the safe recycling of air and water and the reclamation of human wastes. The development of regenerative life support technologies is the only way to eliminate prohibitively costly or impractical resupply during long duration missions. This has been identified as a critical technology area for exploration because of the health requirements of the explorers and the overwhelming costs involved with an open-loop system.

The Regenerative Life Support Program will seek innovative solutions to these challenges to develop closed integrated life support systems. These efforts must include the development of autonomous systems to detect and control microbial and chemical contaminants in air and water recycled from human wastes, closed integrated ground-based and space-based system tests, and the development and conduct of humans-in-the-loop integrated life support systems tests to validate the technologies.

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3. Technology needs for artificial gravity to ameliorate the effects of long-term exposures to low gravity are discussed in Section 2.3.

Radiation Protection

Radiation is a major hazard for travelers in space. For example, the trapped particles in the Earth's Van Allen radiation belts present a natural hazard to astronauts leaving from or returning to low Earth orbit. Effective shielding against the natural radiation environment of space must be implemented. However, each extra pound of shielding mass on a spacecraft or a surface system requires a greater increase in propellant mass. Shielding requirements must be accurately predicted because we cannot afford the costs of superfluous spacecraft or surface system mass for shielding. Unfortunately, based on current data bases and analytic models, estimates of required shielding can vary by a factor of 10:1 or more. (In the case of a Mars Transfer Vehicle, the predicted required mass for shielding varied in one study from 130,000 to 1.8 million pounds, approximately. If 1.8 million pounds were required for shielding, this would be greater than the mass of the remainder of the vehicle.) Resolving these enormous uncertainties in radiation protection is critical to exploration.

A new research and technology program is needed in this area to provide radiation shielding databases and technologies for future human Mars exploration mission options. The Radiation Protection Program will develop analytical models of radiation behind shielding and provide preliminary development of reduced mass shielding system technologies. The program will be integrated with other Agency research associated with biological effects of radiation and models of the predicted radiation environment. [4]

Extravehicular Activity

Extravehicular activity (EVA), the ability of crew members to leave pressurized vehicles and modules and operate locally on the planetary surface, will form a crucial aspect of planetary surface exploration. Key technical issues include: reducing the weight of the suit and portable life support system, suit flexibility and ease of use, and long-duration operability (e.g., up to eight hours per EVA, with local, rapid servicing and regeneration of suit systems between uses).[5] Advances in EVA technology will be enabling for many of the mission options being considered for exploration. An existing focused research and technology program requires refinement and augmentation to meet the needs of exploration.

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4. For example, this research and technology program will be coordinated with the results of the Lifesat space sciences program currently under study.

5. The current state-of-the-art Space Shuttle suit requires a relatively large number of ground-based servicing hours for every hour of EVA; this level of servicing needs to be reduced to support EVA beyond low Earth orbit - for example, at a Lunar Outpost.

In the near-term, the Extravehicular Activity Program will develop critical surface space suit systems, such as suit materials, dust protection, and mobility mechanisms. It will include the development of portable life support systems, end-effectors and tools, as well as the preliminary definition of detailed requirements and plans for EVA systems technology breadboards and testing.

Exploration Human Factors

Human factors, including both human performance and machine interfaces, will play an integral role in the long-term efficacy of all exploration initiative operations. Significant technological advances will provide high leverage for exploration systems by increasing crew effectiveness safely. An existing focused national research and technology program must be refined and augmented to meet the needs of exploration.

Near-term efforts in the Exploration Human Factors Program will develop virtual presence systems for exploration, models of human performance under exploration-relevant conditions to support future exploration system design, and human-machine system interfaces (including breadboard workstations and artificial intelligence-based astronaut assistants).[6]

6. This program will be coordinated with the results of ongoing and planned psychosocial studies in the NASA life sciences program.

SECTION 2.7

Lunar and Mars Science

Many exciting scientific programs will be conducted as part of the Space Exploration Initiative, including local planetary science studies (e.g. investigations of Mars) as well as use of systems and sites at the Lunar Outpost to accommodate space physics and astrophysics instruments. These scientific objectives are being assessed for technology development as follows:

- *in situ* planetary sampling (in some cases for return to Earth laboratories for analysis)
- planetary probes and penetrators for local science
- technology for astrophysics observatories

Sample Acquisition, Analysis and Preservation

The capability to acquire, analyze and preserve samples of planetary surface materials for subsequent return to Earth laboratories, is an important long-standing objective of the planetary science community. The Sample Acquisition, Analysis and Preservation Program will accelerate and diversify the development of technologies for planetary sampling, including sensors, sampling mechanisms and tools, preservation canister requirements, materials and configurations, and definition of integrated breadboard demonstrations. Technology developments in this key area of science may also support Initiative operational requirements - such as Lunar Outpost site certification and prospecting for lunar resources prior to the initiation of *in situ* resource utilization.

Probes and Penetrators

A global network of surface stations is an integral part of our present strategy for the exploration of Mars; these stations would be small, potentially long-lived landers (possibly including subsurface penetrators) that could be deployed from an orbiting spacecraft. A new research and technology program is needed in this area to provide the technologies for this type of robotic Mars exploration mission option. The Probes and Penetrators Program will develop the various component technologies required for capable, small planetary probes and their demonstration as appropriate, including innovative decelerator concepts, compact communications, impact-resistant materials and structures, and power supplies, and the capability for deep subsurface penetration.

Longer-Term Science Technology Needs

In the long term, establishing and operating astrophysical observatories will be a key objective of the Lunar Outpost and will entail major engineering and technological challenges. These challenges may include:

- precision observatory systems construction
- large, precision - but low-mass - reflector panels
- lunar observatory sensors and sensor subsystem technologies

Development in advanced technologies will be enabling for lunar-based observatories. However, in FY 1991, no focused program is planned in this area due to projected timing for implementation of lunar observatories and the relative immaturity of technology requirements definition. Lunar and Mars science mission options are under study. Corresponding technology needs and development plans will be reassessed and updated during the course of the Space Exploration Initiative.

SECTION 2.8

Information Systems and Automation

The payoffs from lunar and Mars science activities will depend on the available capabilities to communicate their results back to Earth. The scope and reliability of exploration operations similarly will depend on local data processing systems and the level of local automation. In almost all of the systems being projected for exploration, advances in cross-cutting technologies in the area of information systems and automation have the potential to substantially improve reliability, reduce the cost and increase performance of all systems. Technology areas in which advancements are needed, or could provide substantial improvements in mission performance, include:

- high rate communications
- exploration mission automation and robotics
- exploration data systems
- planetary photonics

High Rate Communications

At interplanetary distances, the rate at which scientific and engineering data are communicated directly affects the reliability, performance and return from all space systems operations. Increases in data transmissions capacity and reductions in operations costs will have high-leverage in improving Lunar Outpost operations. These same improvements in communications technology will be enabling for many of the systems being considered for Mars exploration. (For example, technologies for increased data rates would allow fully capable television transmissions to and from astronauts on Mars.)

There presently is no focused research and technology program in this area. However, one is needed to provide the technologies for advanced communications systems for piloted and robotic, lunar and Mars, exploration missions. The High Rate Communications Program will support the development and demonstration of high-rate lunar and Mars communications technology, including an initial Ka-band frequency communications capability and a subsequent optical frequency communications capability. Also supported will be technology development for untended system operations for efficient management and reliable operations of exploration telecommunications, navigation and information management resources.

Exploration Automation and Robotics

Implementation of a multi-decade exploration program will require an equally far-sighted strategy for automation and robotics (A&R) investments. Although it is clear that automation and robotics technology will be essential to the success of the Space Exploration Initiative, investments in A&R must be carefully coordinated with the overall Exploration Technology Program. First, functionally-oriented focused development must be pursued in many areas. (For example, the Planetary Rover Program within the Surface Operations Thrust must incorporate A&R technologies for surface mobility and navigation.) In addition, there is a need to maintain innovation in devising A&R applications to Exploration, as well as to develop selected, common A&R capabilities. Many of these - such as standardized robotic manipulators for surface operations - will be enabling for some exploration systems.

A new research and technology program is needed to provide innovative and common automation and robotics technologies for a range of lunar and Mars exploration mission options. This program will begin the development of commonly required A&R technologies and subsystems. In some cases, these A&R capabilities will be provided for demonstration in other element programs within the Exploration Technology Program. These will include advanced artificial intelligence-based system executives, vision subsystems and generalized surface robotic manipulator systems.

Exploration Data Systems

Today's state-of-the-art space data systems will not meet the projected needs of the Space Exploration Initiative. Highly capable, space-qualifiable data systems for exploration mission systems applications must be developed for high data rate needs; these will be high leverage for lunar outpost applications and can serve as demonstrations for later use in Mars missions, and will be enabling for many robotic and human Mars exploration vehicles and systems. Efforts in this general area will build on a foundation of data systems technology development for the nearer-term Earth Observing System (EOS).

Areas for exploration development include system architectures, data processors, recorders for mass data storage and data compression algorithms and hardware. In addition, field and flight testing of selected technologies will be required. Exploration Data Systems technology requirements that are different from the capabilities being developed for EOS are being defined and a program in this area is being planned. This preliminary technology planning will evolve as new approaches to meet exploration data system needs are identified and requirements are further refined.

Planetary Photonics

In photonics, a specialized area for potential exploration data systems, high-leverage opportunities for data and sensor systems have been identified. Photonics-based systems incorporate computer or sensor chips that use photons in lieu of electrons for processing functions. Despite advances in computing technologies using purely electronic components, the power, mass and volume limitations of flight systems typically preclude the use of these components for many applications. The trade that results frequently forces early downscoping of system performance, and hence downscoping of overall mission performance. This situation will be of particular concern for exploration systems. In a variety of applications, however, data or sensor systems that are hybrids of electronic and photonic components can be high-leverage for key systems by providing very high performance at much lower power, mass and volume than comparable all-electronic systems.

A new focused research and technology program is needed in this area to provide high performance technology options for robotic Mars missions, and for possible lunar applications. This program will begin the development of selected photonics-based subsystems for exploration applications, including multispectral image processing and high-speed hazard detection processing.

SECTION 2.9

Nuclear Propulsion

As discussed in Section 2.3, space transportation is a primary part of all planning for exploration. Existing chemical reaction-based space propulsion systems - like combustion engines in terrestrial applications - are limited in the amount of performance they can provide for exploration vehicle transportation, with concomitant lengthy trip times and high-launched mass requirements. While these limitations have manageable consequences for Earth-Lunar transportation, the consequences are far more severe for Earth-Mars vehicles, given their high performance requirements. The high-performance propulsion capabilities that can be provided by non-chemical, nuclear energy-based systems could substantially reduce exploration flight times to and from Mars and reduce launched mass requirement.

For example, nuclear propulsion may be capable of off-setting hundreds of thousands of pounds of vehicle mass for each flight, as well as cutting flight times in half. Nuclear propulsion, therefore, is considered a critical major technology alternative to more conventional space transportation technologies for exploration. The Exploration Technology Program strategy with regard to nuclear propulsion is to conduct parallel development in several major technologies, within the areas of nuclear thermal propulsion and nuclear electric propulsion, with down-selection on promising concepts for further development as research and testing warrant.

Nuclear Thermal Propulsion

Nuclear thermal rockets use a nuclear reactor to directly heat a working propellant for moderately high specific impulse, very high thrust propulsion. Potential classes of such nuclear thermal rocket propulsion systems include solid core, liquid core and gaseous core nuclear reactors. Of these, solid core reactor systems have the greatest level of technological maturity (they are based on extensive development conducted during the 1960s and early 1970s). However, gas core nuclear thermal rockets promise the greatest potential mission benefits, in terms of dramatically reduced flight times and somewhat reduced initial launched mass requirements.

A new research and technology program is needed in this area to support the overall Exploration Technology Program strategic goal of providing a validated, nuclear propulsion technology option for human Mars exploration missions. The Nuclear Thermal Propulsion Program will develop and test key technologies required to determine the feasibility of large-scale future nuclear thermal rocket propulsion concepts for potential application in Earth-to-Mars transportation systems.

Nuclear Electric Propulsion

Nuclear electric propulsion concepts employ a nuclear reactor to generate the electricity that is used to drive electric thrusters for very high specific impulse, low to moderately high thrust propulsion. Nuclear electric propulsion systems promise the greatest potential mission benefits in terms of dramatically reduced initial launched mass requirements, with the potential for moderate improvements in Earth-to-Mars flight times.

A focused research and technology program is needed in this area to support the overall Exploration Technology Program strategic goal of providing a validated, nuclear propulsion technology option for human Mars exploration missions. The Nuclear Electric Propulsion Program will develop the technologies required for extremely high-specific impulse[7], low-to-moderate thrust electric propulsion, using nuclear power systems as the source of electrical energy.

7. A high specific impulse means that the propulsion system uses each pound of propellant more efficiently - i.e., to produce a greater change in its velocity per pound than those systems with lower specific impulses.

SECTION 2.10

Innovative Technologies and Systems Analysis

Definition and management of a long-term, focused technology development effort such as the Exploration Technology Program, requires the continual reevaluation of ongoing work, the integration of diverse activities throughout the program, and the incorporation of new ideas into the program. All elements within the Exploration Technology Program will be involved in seeking and demonstrating effective and innovative approaches to meeting exploration mission needs.

As discussed in Section 2.2, an integral part of the Exploration Technology Program approach will be the continual search for innovative concepts from across the Nation. NASA plans to "cast our net widely drawing upon America's creative potential to ensure that we are benefiting from a broad range of ideas," including new technologies and innovative uses of existing technologies. This thrust in the Exploration Technology Program will include studies and research to determine the feasibility of high pay-off new technology concepts.

In addition, it is crucial that new technological concepts and options be assessed one against another in terms of their potential to benefit the Space Exploration Initiative. Once identified, systems analysis studies will be needed to determine mission application feasibility and requirements for future inclusion, where appropriate, of new technology concepts as demonstrations in Exploration Technology Program elements. This thrust in the Program will conduct independent analyses and assessments to determine optimum performance approaches, and will develop techniques and tools for program management and integration.

SECTION 2.11

Exploration Technology Summary

The Exploration Technology Program will make possible the implementation of a broad range of exciting Solar System exploration missions. The scope of the Space Exploration Initiative's objectives and the range of areas in which technology development is needed make the problem of summarizing technology applications quite complex. Figure 2-1 offers such a summary, recapitulating the current assessment of how these technologies are applicable to the needs of the Space Exploration Initiative (including sufficient scope to address multiple architectural options). Within Figure 2-1, technology program areas are scored according to the currently understood importance of their application to parts of the Space Exploration Initiative (robotic and human phases of establishing a Lunar Outpost, and robotic and human phases of the exploration of Mars).[8] Obviously, not all technology areas are as timely for all parts of the Initiative.

Where there is no circle in a given mission column, there is no currently known significant application of that technology program area to that part of the Initiative. An unfilled circle (i.e., " ⊖ "), indicates that the technology area listed is, at present, projected to provide high leverage to systems in that part of the Initiative but, is not enabling to the design and development of those systems. For example, major technological advances in the area of high rate communications could substantially improve the reliability of outpost data systems and increase the data return from outpost science missions, but if the new technologies were not available, an outpost's communications system could still be implemented (albeit with poorer performance, lower reliability, higher costs, etc.).

Similarly, a half-filled circle in a mission column (i.e., " ◓ ") indicates that significant advances in that technology area are viewed as enabling, or absolutely necessary, to design and develop some of the key systems in that part of the Exploration Initiative. For example, the kinds of mobile robot systems being envisioned for use in the robotic exploration of Mars will not be possible without the technology developments being pursued within the Planetary Rover element program. Although a limited robotic Mars exploration program of some sort still could be conducted, the kinds of roving science laboratories that planetary scientists envision for this challenging mission would not be possible.

Notice that some technologies are enabling for some systems in one part of the Space Exploration Initiative, but only high-leverage for another part. These subtle differences in ratings reflect our current understanding of the specifics of

8. In addition, for reference the applicability of these Exploration Initiative technologies to other space science missions is shown in the column at the far right. For a discussion of what missions this column includes, see Chapter 5.

the possible mission design options in each area and the importance of a given technology development to those specific options.

Finally, a few of the circles in some of the columns are completely filled (i.e., " ● "). In these cases, the technological advances that are possible in these areas are of such significant benefit for major Initiative objectives that they are critical to the overall success of the Program. For example, in a typical case, using aerobraking for lunar outpost transportation can result in a savings of approximately 150,000 pounds per year in mass required in low Earth orbit (e.g., for propellants). Hypothetically, if one assumes Earth-to-orbit transportation costs can be reduced from approximately $3,000 to $6,000 per pound (for current Titan launch vehicles) to $500 to $1000 per pound (by employing low-cost, heavy-lift launch vehicles), developing and using aerobraking could be worth $75,000,000 to $150,000,000 in savings per year.

As Initiative goals and mission designs are refined, and as innovative concepts are identified in the various technology areas, assessments will be reexamined.[9]

9. In the special case of Mars transportation, two competitive - or perhaps synergistic - technology options are shown as "critical": Aerobraking with Space-Based Engines, and Nuclear Propulsion. Although NASA believes that the former, more conventional, technologies can be used, if Nuclear Propulsion were available it would substantially reduce mission costs and risks.

TECHNOLOGY THRUST	TECHNOLOGY PROGRAM AREA	Lunar Outpost ROBOTIC	Lunar Outpost HUMAN	Mars Exploration ROBOTIC	Mars Exploration HUMAN	Other Solar System Exploration Applications
Earth-To-Orbit	Propulsion, Avionics, Manufacturing		●	⊖	●	◓
Space Transportation	Aerobraking		●	●	●	◓
	Space-Based Engines		●	⊖	●	⊖
	Autonomous Landing		◓	◓	◓	◓
	Auto. Rendezvous & Docking		◓	◓	◓	◓
	Vehicle Structures & Cryo Tankage		⊖	⊖	◓	⊖
	Artificial Gravity				◓	
In-Space Operations	Cryogenic Fluid Systems		◓		◓	
	In-Space Assembly & Construction		◓		◓	⊖
	Vehicle Servicing & Processing		◓		◓	⊖
Surface Operations	Space Nuclear Power	◓	●	◓	●	◓
	In Situ Resource Processing		●	⊖	●	
	Planetary Rover	◓	◓	◓	◓	◓
	Surface Solar Power	⊖	◓	⊖	◓	◓
	Surface Habitats & Construction		◓		◓	
Human Support	Regenerative Life Support		●		●	
	Radiation Protection		●		●	
	Extravehicular Activity Systems		◓		◓	
	Exploration Human Factors		⊖		⊖	
Lunar & Mars Science	Sample Acq. Analysis, & Preserv.	◓	⊖	◓	⊖	◓
	Probes & Penetrators			◓	⊖	◓
	Astrophysical Observatories		◓			⊖
Information Systems & Automation	High-Rate Communications	⊖	⊖	◓	◓	◓
	Exploration Automation & Robotics	◓	◓	◓	◓	◓
	Planetary Photonics	⊖	⊖	◓	⊖	⊖
	Exploration Data Systems	⊖	⊖	◓	◓	◓
Nuclear Propulsion	Nuclear Thermal Propulsion				●	◓
	Nuclear Electric Propulsion				●	◓

LEGEND ⊖ High-Leverage Technology ◓ Enabling for Some Exploration System Options ● Critical Exploration Initiative Technology

FIGURE 2-1 Exploration Technology Needs Summary Projection (Including Robotic and Piloted, Lunar and Mars Missions, and Possible Secondary Applications to Other Space Science Missions)

CHAPTER 3

Exploration Technology Program Resources

Human exploration demands an investment in exploration technology that has both the breadth and depth to insure that the best possible engineering choices can be made in finalizing system designs and that the overall program substantially strengthens advanced technologies in the U.S. Figure 3-1 provides an overview of the Exploration Technology Program work breakdown structure (including element programs that are projected but not planned for initiation in FY 1991), as well as related activities in the Civil Space Technology Initiative.

Figure 3-2 provides the President's FY 1991 Exploration Technology Program budget, along with resources required for exploration-critical element programs in the Civil Space Technology Initiative. Program planning and the future resources required for program implementation will continue to be developed and refined as mission studies mature and as innovative technology options for exploration are identified and incorporated into plans.

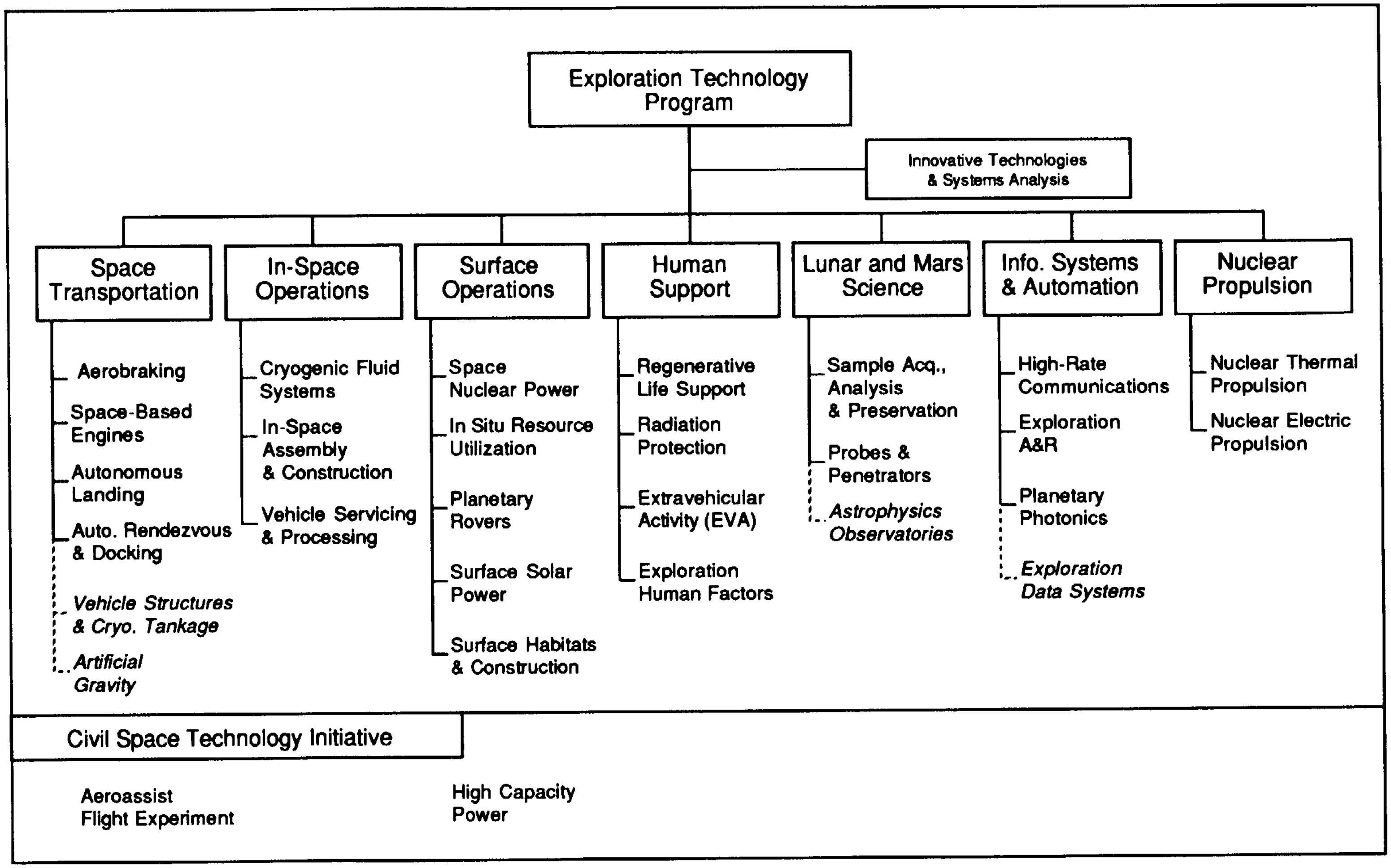

Figure 3-1 Exploration Technology Program Work Breakdown Structure; Including Critical Elements of the Civil Space Technology Initiative. [Note: Elements in Italics are Being Planned for Initiation After Fiscal Year 1991]

Exploration Technology Program	FY 1991 [$, Millions]
	179.4
SPACE TRANSPORTATION	38.0
IN-SPACE OPERATIONS	23.0
SURFACE OPERATIONS	62.0
HUMAN SUPPORT	25.4
LUNAR AND MARS SCIENCE	4.5
INFORMATION SYSTEMS & AUTOMATION	10.5
NUCLEAR PROPULSION	11.0
INNOVATIVE TECH. & SYSTEMS ANALYSIS	5.0
Civil Space Technology Initiative	
Aeroassist Flight Experiment	70.0
High Capacity Power	11.1

Figure 3-2 Exploration Technology Program FY 1991 Resources Requirements; Including Exploration-Critical Elements of the Civil Space Technology Initiative

CHAPTER 4

In-Space Technology Development

The majority of research and technology development activities required to provide a foundation of capabilities for the Space Exploration Initiative can and will be conducted in ground-based laboratories and facilities. However, in many cases technology developments must be tested and validated in space because no terrestrial facility can adequately simulate key physical and operational characteristics of the space environment. Each of the several development areas of the Exploration Technology Program may involve some degree of in-space experimentation. Some of these will be free-flying experiments launched from expendable launch vehicles or from the Space Shuttle. For example, aerobraking is planned to be used for human expeditions to Mars, both at Mars and at Earth return. In this case, flight experimentation will be needed for simulation of the very high velocity entry into the Earth's atmosphere. This entry would be experienced by a spacecraft returning from Mars. Such an experiment would build directly on the flight experience gained from lunar outpost operational aerobraking and would be integrated with robotic Mars mission aerobraking.

In addition, current planning calls for significant in-space technology experimentation to be conducted on Space Station *Freedom*. The technologies that most require testing and validation in Earth orbit are in the area of in-space operations, such as assembly and construction techniques. These techniques include mating major space components (e.g., assembling segments of the lunar transfer vehicle aerobrake or integrating cryogenic tankage for that vehicle) and structure inspection and adjustment of vehicle components following each mission. Vehicle processing technologies, including inspection and integration of payloads, and largely-automated check-out and testing of integrated vehicle systems and payloads will be tested on the Space Station. Research and technology development may also be extended to the on-orbit environment to test processes and subsystems for regenerative life support systems needed for advanced lunar outpost systems and for Mars transfer vehicles. Planning for these activities, and the requirements that may be placed on *Freedom* to accommodate them, are being actively coordinated with the Space Station program.

Once operations begin at a Lunar Outpost, this facility will be used to conduct needed in-space technology development efforts. The focus of these experiments will be on development of advanced capabilities for the Lunar Outpost itself, or toward the testing of technologies and systems that subsequently would be applied for human expeditions to Mars. For example, during the early years of a Lunar Outpost, *in situ* experiments may be needed to validate specific operational concepts for *in situ* resource utilization prior to final fabrication of flight systems. In the case of testing for Mars, an example could be in the area of extravehicular activity systems. Where realistic operational and surface conditions are needed, advanced suit technologies (such as astronaut-suit interfaces or surface mobility concepts) may be tested at the Lunar Outpost. In-space technology development on the Moon will provide a special capability in which the outpost program can leverage itself - allowing one phase of the Initiative to build toward the next - and accelerate the development and implementation of more self-sufficient and higher performance systems for both the Moon and Mars.

CHAPTER 5

Other National Technology Development

SECTION 5.1

National Technology Resources

The development of technology for piloted Solar System exploration missions will be an ambitious endeavor. The Exploration Technology Program is a national effort. This program must be well coordinated with, and use, wherever advantageous, advances in engineering capabilities that are being achieved by other national technology development programs. Programs such as the Advanced Launch Development (ALD) program will provide key advances in Earth-to-orbit transportation that could directly support exploration in the next century. In addition, the ALD and the National Aerospace Plane (NASP) Programs are developing technologies which also may have exciting applications elsewhere within exploration activities, including advances in guidance, navigation and control, vehicle materials and structures, and propellant tankage. Similarly, the Earth Observing System program will drive the development of systems (in areas such as data management) that will be applicable to exploration.

Significant space technology expertise resides in institutions and programs outside of NASA. Numerous universities, including the participants in the NASA University Space Engineering Research Center program, have extensive experience in space technology research and application. This includes expertise in exploration technology areas such as local planetary resource processing, aerobraking and advanced space engine health monitoring. The Defense Advanced Research Projects Agency (DARPA) is continually developing new, innovative applications of microelectronics, software and sensors. One of that agency's programs, the Advanced Land Vehicle, has provided a substantial portion of the technological foundation upon which NASA has pursued recent planetary rover development.

Similarly, other Department of Defense organizations provide important capabilities and expertise. Innovation and excellence are hallmarks of the Department of Energy's national laboratories, including the Idaho National Engineering Laboratory, Lawrence-Livermore, and others, and they will be strong contributors of technology for human exploration missions. For example, the Los Alamos National Laboratory is collaborating with NASA in the development of energy technologies for exploration, including research in regenerative fuel cells. Los Alamos has a major role in the nation's major space nuclear power program (the SP-100 Ground Engineering System Project), which is led by the Jet Propulsion Laboratory.

The Space Exploration Initiative will be a national endeavor, involving NASA, national laboratories, industry and universities. The development of technology for exploration of the solar system - establishing an outpost on the Moon and the exploration of Mars - will challenge the Nation.

SECTION 5.2

Other Mission Applications

In addition to the missions being planned directly as part of the Space Exploration Initiative, there are also diverse ambitious space science robotic exploration missions being studied by NASA. These missions require advances in many of the same capabilities that are needed for the Initiative. Meeting the direct mission needs of the Initiative will benefit a wide range of future robotic space science missions. Thus, the space technology development investment made for the Initiative can be leveraged to offset the costs and risks of other worthwhile endeavors in space.

Finally, as ambitious as the objectives of the Exploration Initiative are, they do not encompass all of exploration, The expansion of human presence and activity into the Solar System will not end with the first piloted mission to Mars. It will only have begun. The investments made in exploration technologies within the Exploration Technology Program will support future space policy goals beyond the specific objectives of the Space Exploration Initiative.

SECTION 5.3

National Technology Benefits

Because the objectives of the Space Exploration Initiative are ambitious, the Exploration Technology Program must encompass the development of a broad range of new technologies and engineering expertise to meet exploration mission needs. The Mercury, Gemini and Apollo programs inspired thousands of new science and engineering graduates and drove advances in electronics miniaturization and new materials. Similarly, the space program drove the development of NASA expertise in power systems which was brought to bear to help research possible solutions to National energy problems in the late 1970s. In the same way, the Space Exploration Initiative, and in particular the Exploration Technology Program, will produce capabilities and expertise that will benefit the U.S. and its economy.

Terrestrial applications of exploration technology will be one such benefit. The U.S. commercial sector will profit from diverse developments in high-leverage areas such as Planetary Photonics (with low-cost, highly capability data processing), Exploration Human Factors (with advanced human-machine interfaces), Surface Solar Power (with progress in photovoltaic solar arrays and regenerative energy storage) and Exploration Automation and Robotics (with innovative new concepts - for example in dexterous robotic manipulator systems - that could have broader applications).

The transfer of new, high-leverage technologies to the broader economy will be facilitated by appropriate industry participation in exploration technology planning and by possible private Exploration Initiative investment. The U.S. aerospace industry - including private space ventures - will benefit from developments in high-performance Space-Based Engines and Autonomous Vehicle Maneuvering that can be used in future commercial space vehicles, and advances in Vehicle Structures and Cryogenic Tankage that could reduce manufacturing and operations costs for such vehicles. Finally, many of the technologies developed for the Space Exploration Initiative will also benefit the ongoing objectives of U.S. space science programs - including scientific efforts in areas as important as basic life sciences research, astrophysical studies of the cosmos, studies of the sun and Earth's space environment, as well as future planetary exploration missions such as the Voyager mission that flew by Neptune in the Summer of 1989.

CHAPTER 6

Summary

Returning to the Moon to stay, pursuing robotic and human exploration of the planet Mars, and continuing the exploration of the Solar System, are ambitious objectives. A significant, long-term investment in technology is required to achieve these objectives. There is a strong foundation of planning for exploration technology development, including processes to find and incorporate new and innovative approaches to meeting the challenges of exploration. The Exploration Technology Program has been designed to provide the United States with the capabilities essential to establish an Outpost on the Moon early in the next century, and for the robotic and human exploration of Mars.

The development of exploration technology will have significant implications for the United States. Over the past several years, a national consensus identified the need for a significant investment in space technology development.[1] The Exploration Technology Program will direct the broad-based investments toward cutting-edge aerospace technologies, identified as crucial to the long-term competitiveness of the American aerospace industry. In addition, a strong research and technology program for exploration will involve extensive university participation. This will provide a strong impetus to U.S. education and university research programs. The Exploration Technology Program will reach the young, through the excitement and sense of progress that these technologies generate and the aspirations they inspire. The applications of exploration technology will affect our everyday lives and improve our Nation's economy. Finally, a strengthened investment in space research and technology is necessary to ensure lasting U.S. leadership in civil space exploration.

The Space Exploration Initiative will be a national endeavor, involving the Nation's entire aerospace science and engineering community: NASA, national laboratories, industry and universities. The development of the technologies needed for exploration will challenge the Nation with new standards of achievement in education, innovation in research, and excellence in engineering and manufacturing. The Exploration Technology Program is an essential element of the development of the Space Exploration Initiative.

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1. A number of groups have recommended a strong increased investment in space research and technology, including the National Commission on Space, NASA's Space Leadership Planning Group, the Aerospace Industries Assoication (which identified key technologies for the aerospace industry in the 1990s), the American Institute of Aeronautics and Astronautics, and the National Research Council.

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